PHOTOINJECTOR BASED MeV ELECTRON MICROSCOPY

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Abstract

A time-resolved MeV electron microscopy based on a photocathode rf electron gun is being developed in Osaka University to reveal the hidden dynamics of intricate molecular and atomic processes in materials. A new structure rf gun has been developed to generates a high-brightness femtosecond-bunch electron beam. The microscopy has been used successfully for the single-shot MeV electron diffraction measurement and the time-resolved measurement. The transverse emittance, bunch length and energy spread were diagnosed as the functions of the laser injection phase, the laser pulse width and the bunch charge. The growths of the emittance, bunch length and energy spread due to the rf and the space charge effects in the rf gun were investigated.

INTRODUCTION

Research into ultrafast dynamic processes of chemical/physical reaction have been largely investigated using femtosecond laser pump-probe, or femtosecond laser pump and short-pulsed X-ray radiation probe, or ultrashort-bunch electron beam pump and femtosecond laser probe techniques [1-3]. Many hidden dynamics of intricate atomic processes or ultrafast chemical/physical reactions have been revealed in material science, physics, chemistry and biology. Recently, a technique of ultrafast electron diffraction (UED) has been developed for the study of the dynamics of ultrafast processes in material systems [4,5].

While the techniques are the powerful tools for sensing the dynamic and spectrum of atomic/molecular spacing in the sampled volume, there are many scientific investigations that benefit from real-space imaging, e.g. in nanometre space or range. A method of ultrafast electron microscopy (UEM) has been developed for monitoring the imaging of the specimen with time-resolved. The imaging affords a more direct interpretation of the defect structure than does diffraction. Currently, the UEM with the nanosecond time resolution has been achieved in conventional TEM through the use of photo-activated electron source driven by a nanosecond laser [6]. To obtain a high time resolution, a stroboscopic imaging of periodically driven processes [7] was preformed. In this configuration, a time resolution of 200 ps was achieved for processes up to 100 MHz, which called the single-electron-pulse method. These techniques were applied to ultrasonically driven disruption of crystals and magneto-elastic effects and magnetic-field-induced oscillations of the domain magnetization of domain walls and of their substructures. However, there is no resolution to obtain a femtosecond-temporal and nanometer/sub-nanometer-spatial resolution in UEM, because of the electron bunch length and bunch charge due to the space-charge effect.

In order to reduce the space charge limitation, a MeV photocathode rf electron gun based relativistic energy based UED was firstly considered in 2006[8]. In the photocathode rf guns, the electrons emitted from the photocathode surface are accelerated rapidly with a strong rf electric field (~100 MV/m or more) to reach relativistic speeds within a few millimeters. The increases in the pulse duration, emittance and energy spread due to the space charge effect are thus reduced to the minimum. A rf gun based ultrashort electron beam at the energy of 1~3 MeV, the emittance of 0.1 mm-mrad, the bunch length of 100 fs and the electron charge of ~1 pC is approached in Osaka University [9]. From 2006, several groups have developed and demonstrated new MeV UED systems using the photocathode rf guns [10-12]. The single-shot measurement has been also succeeded. The studies indicate and suggest that the photocathode rf gun is useful for the UED technique to achieve a high time resolution of the pump-probe measurement. Recently, a femtosecond time-resolved MeV electron microscopy using the rf gun has been proposed in Osaka University to study the atomic dynamics of phase transitions in solids. Here, we report the developments of a near-relativistic femtosecond electron rf gun and the design of a MeV UEM system using the photocathode rf gun. The results of beam diagnostics of femtosecond electrons in the rf gun and the demonstrations of MeV electron diffraction and imaging measurements are presented.

TIME-RESOLVED MEV ELECTRON MICROSCOPY

The system of time-resolved MeV electron microscopy using the rf gun in Osaka University is shown in Fig.1. A photocathode rf gun driven by a femtosecond laser is used to generate a low-emittance, low-energy-spread femtosecond electron beam. The beam is passed through a solenoid magnet, and then guided to an alpha magnet with a energy filter to select a required energy spread beam. After the alpha magnet, two condense lenses, an objective lens, an intermediate lens, a projector lens and an imaging system are used to the MeV imaging measurement. The characteristics of the electron beam generated from the rf gun can be determined in the single-shot UEM using an efficient 1000 x 1000 pixel charge-couple device (CCD) camera with 25 μm pixels:

(1) According to the Rose criterion (~100 electrons/ pixel), the number of electrons in the bunch can

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be considered to N~10^8 for the imaging and N~10^6 for the diffraction.

(2) The normalized emittance of the electron beam generated from the rf gun is required to less than 0.14 mm-mrad for obtaining a focal spot size of 10 μm on the specimen.

(3) The energy spread should be of order of 10^{-4} to reduce the effects of spherical and chromatic aberrations in the electron optics.

(4) The final requirement is low dark current from the rf gun.

In order to achieve these requirements, a new 1.6-cell S-band rf gun has been developed under the KEK/Osaka University collaboration with many improvements: (1) a spherical shape cavity was used in both the half and full cells; (2) the conventional laser injection ports in the half cell were removed to reduce field asymmetries; (2) a new turner system was designed to adjust precisely the electric field balance in the half and full cells; and (3) a new insertion function of the photocathode was installed to reduce the field emission. The asymmetry on the rf field is reduced to be minimum in geometry. The emittance growth due to the field-asymmetry is expected to be improved. The dark current from the rf gun is also expected to be reduced. The rf gun is driven by a femtosecond Ti:Sapphire laser. The pulse energy of the ultraviolet (UV) light is 40 μJ in the maximum. The pulse width of the UV light is 200 fs in FWHM. The femtosecond UV light is injected on the cathode surface at an incident angle of approximately 2° along the direction of the electron beam using a vacuum mirror placed downstream of the gun. To achieve a small focal spot size of the electron beam on the specimen, the back-injection method and a transmission cathode is also approached in UEM system. The copper photocathode is considered.

As the experiences, there is no problem to generate the required electron number using the new rf gun. The dark current can be reduced down to <0.1 pC per pulse with the above improvements in the new rf gun. However, at the level of <1 mm-mrad in the rf gun, the emittance can be affected by a number of small contributions like field asymmetries or the thermal emittance of the electrons at the cathode, especially for the thermal emittance. To reduce the thermal emittance, we used a small laser spot size on the cathode.

BEAM DIAGNOSITICS OF FEMTOSECOND ELECTRON BEAM IN RF GUN

In the electron bunch charge measurement, a current transformer (CT) was used. It located at the gun exit and was calibrated with a picoammeter. In the emittance measurement, transverse emittance was measured with a standard quadrupole scan technique, in which the beam size on a 100-μm-thick YAG screen was varied by the quadrupole magnetic field. The electron beam profile on the screen was acquired by a charge-coupled device (CCD) camera with a background subtraction and 3×3 median filter processes, which reduced sharp noises with a beam profile shape maintained. The emittance was calculated by fitting the square of the beam size as a function of the inverse of the quadrupole focal length.

In order to measure the bunch length and the longitudinal beam dynamics of the MeV electron beam produced from the rf gun, we installed a booster linac at the downstream of the rf gun and a 45°-bending magnet at the downstream of the linac. Finally, the bunch length at the gun exit was measured by a linac phase-scan technique [13], where correlated rms energy spread of the electron bunch was measured. A YAG screen was set at

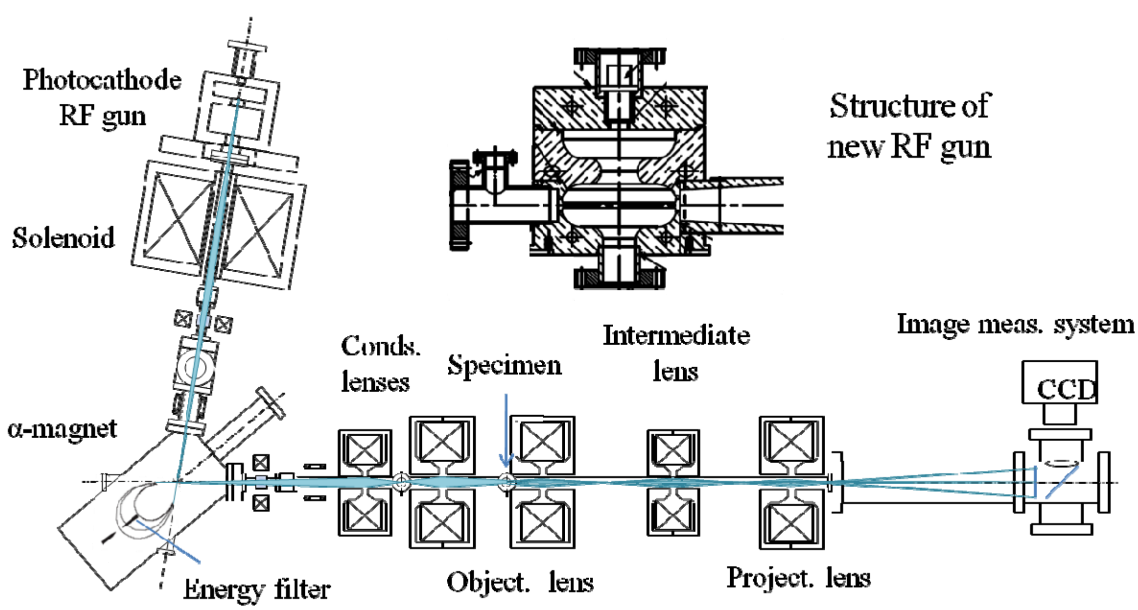

Figure 1: Time-resolved MeV electron microscopy system using the rf gun in Osaka University.

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0.7m downstream of the 45°-bending magnet. The electron beam profile on the screen was acquired by a CCD camera. The linac can give small/large energy modulation to short/long electron bunches. Thus, the bunch length and the longitudinal emittance of the electron beam from the rf gun can be obtained by least-squares fitting of the relationship between the correlated energy spread squared and the accelerating phase in the linac.

First, the normalized transverse emittance was investigated as a function of the bunch charge, as shown in Fig. 2(a). The laser spot radius on the cathode was 0.25 mm. The pulse width of the UV light is 200 fs in FWHM. The magnetic field of the solenoid was a constant of 1.75 kG. The gun phase was 30°. It was found that the space-charge-induced increase of the transverse emittance is 0.067 mm-mrad/pC. The thermal emittance, which is the emittance at zero charge, is thus obtained to 0.16 mm-mrad for the copper cathode with the laser spot radius of 0.25mm. The thermal emittance increases linearly with the laser spot radius with a rate of 0.73 mm-mrad/1mm. Figure 2(b) gives the experimental results. In the case of the bunch charge of <2 pC, the emittance is dominated by the thermal emittance. The data indicates that a low thermal emittance of 0.1 mm-mrad can be obtained with the laser spot radius of less than 100 μm.

Figure 3 gives the obtained longitudinal emittance and the bunch length as a function of the bunch charge. At the bunch charge of <15 pC, the rms bunch length and the longitudinal emittance increase linearly with the bunch charge. The space-charge-induced growth was 27.4 fs/pC for the bunch length and 0.22 deg-keV/pC for the longitudinal emittance. Both the bunch length of 200 fs and the longitudinal emittance of 1.1 deg-keV at zero charge are due to the effect of the injection laser pulse width. The bunch length is determined by the injection UV laser pulse width. The energy spread can be calculated to 2 x 10^{-3}. Anyway, it is possible to reduce the energy spread to 10^{-4} through the injection electron optics of TEM with a condense beam aperture. The use of a short-pulse UV laser (i.e. <100 fs) is also essential to achieve a low-energy-spread electron beam with the bunch length of the order of 100 fs.

CONCLUSION

A time-resolved MeV electron microscopy based on a photocathode rf electron gun has been approached in Osaka University to study the dynamics of photon-induced structure change and electronic/atomic processes in materials. A new structure rf electron gun was developed and expected to generate a 100-fs short-bunch MeV electron beam with the emittance of 0.1 mm-mrad and the energy spread of <10^{-4}. The transverse emittance, bunch length and energy spread were diagnosed as the functions of the laser injection phase, the laser pulse width and the bunch charge. The growths of the emittance, bunch length and energy spread due to the rf effect and the space charge effect in the rf gun were investigated.

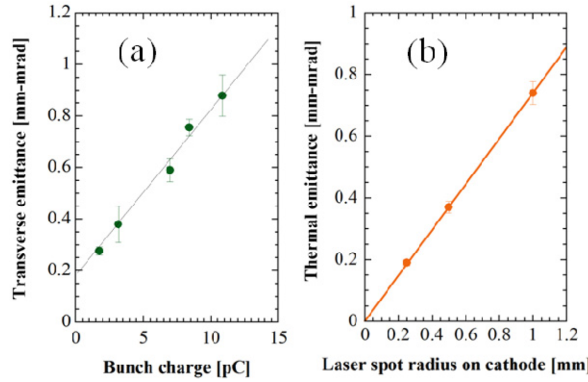

Figure 2: The transverse emittance (a) and thermal emittance (b) as a function of bunch charge and laser spot radius on the copper cathode.

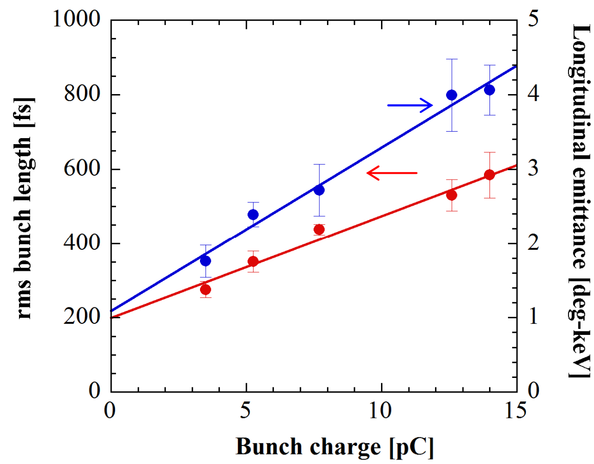

Figure 3: The longitudinal emittance and bunch length as a function of bunch charge.

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